



A Metric and GIS Tool for Measuring Connectivity Among Habitat Patches Using Least-Cost Distances

by Jeff P. Lin¹

PURPOSE: This technical note presents a new landscape connectivity metric, as well as a user's guide for an ESRI ArcGIS® tool that is used to calculate it. This new metric builds and improves on the concept of the proximity index. The tool and metric are specifically intended for measuring changes in connectivity due to the loss or gain of habitat patches and/or alterations in the surrounding landscape. As such, the tool is of particular use when comparing impacts or benefits to connectivity from among various project alternatives.

INTRODUCTION: Landscape connectivity has been defined as “the degree to which the landscape impedes or facilitates movement among resource patches” (Taylor et al. 1993). It is now generally accepted that landscape connectivity plays an essential role in the dispersal of organisms among habitat patches and thus the conservation of biodiversity (Tischendorf and Fahrig 2000). Connectivity can be characterized as either functional or structural; structural connectivity describes only the spatial relationships among habitat patches such as inter-patch distances and the availability of corridors, while functional connectivity measures the ability of organisms to move among patches based on the surrounding landscape (Taylor et al. 2006). Two patches may be separated by only a short distance and thus have a high structural connectivity. However, the functional connectivity of those patches will depend on the nature of the intervening distance and the dispersal characteristics and abilities of the organism being considered. For instance, if the two patches are separated by an interstate highway, then the functional connectivity between them might be quite low for a turtle, but higher for a bird.

Several different metrics have been used to measure connectivity (McGarigal and Marks 1995; Schumaker 1996; Moilanen and Nieminen 2002; Bender et al. 2003; Calabrese and Fagan 2004). When considering a single patch, perhaps the simplest measure of connectivity is the distance to its nearest neighbor (a patch of the same type). When considering multiple patches in the landscape, an average nearest-neighbor score can be used as an indicator of connectivity for the whole group. However, although nearest-neighbor distance is a commonly used connectivity metric, it appears to be a poor predictor of actual species colonization rates; the reasons being that it often ignores patches that are within a reasonable migration distance from the focal patch and that it does not explicitly factor in the size and shape of patches (Moilanen and Nieminen 2002; Bender et al. 2003).

A more robust connectivity metric than simple nearest-neighbor distance is the proximity index, which is defined as the sum of the ratio between patch area and inter-patch distance for all patches within a specified buffer distance around a focal patch (Gustafson and Parker 1994; Bender et al.

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Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE SEP 2008		2. REPORT TYPE		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE A Metric and GIS Tool for Measuring Connectivity Among Habitat Patches Using Least-Cost Distances				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Environmental Laboratory,U.S. Army Engineer Research and Development Center,3909 Halls Ferry Road,Vicksburg,MS,39180				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 15	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

2003). The proximity index offers an advantage over nearest-neighbor distance in that more than one other patch can be considered in relation to the focal patch, and the total area of connected patches is also factored into the equation. However, the metric is still somewhat limited in that it does not measure functional connectivity, and does not consider aspects of patch habitat quality other than patch area. Therefore, as a new alternative and potential improvement to previous methods for measuring connectivity, the “connectivity score” is presented in the following sections.

THE CONNECTIVITY SCORE : The connectivity score is similar to the proximity index in that it is calculated based on weighted distances between patches that are within a fixed buffer distance of one another. However, the connectivity score is potentially a more robust metric in that it encapsulates functional connectivity through the use of least-cost distances between patches, and allows for the incorporation of additional measurements of patch habitat quality.

Euclidean distance is the simplest way to measure inter-patch distances. However, measuring connectivity using the Euclidean distance between patches addresses only structural and not functional connectivity, thereby ignoring the behavior of the migrating species (Taylor et al. 2006). Functional connectivity can instead be measured through the use of least-cost distances (Driesmal et al. 2007; Nikolakaki 2004; Adriaensen et al. 2003; Bunn et al. 2000), and various studies have shown least-cost distances to be a better measure of connectivity than Euclidean distances (Chardon et al. 2003; Coulon et al. 2004). In a least-cost distance analysis, the landscape matrix between patches is viewed as a grid, with each cell in that grid having a specific resistance value or “cost.” Certain land cover types will be less traversable to wildlife than others; therefore, cells containing these cover types will have a higher cost associated with them. The cost distance between two patches is the least accumulated cost associated with a single path (the least-cost path) between the patches (Figure 1).

1	2	2	2	3	3
1	1	2	2	3	3
2	5	5	5	5	3
1	1	1	5	5	5
1	1	1	2	5	5
1	1	3	3	1	1

Figure 1. Cost grid showing the least-cost path (light grey cells) as compared to the Euclidean path (hatched cells) between two focal patches (black cells). The numbers are the movement cost for traversing one linear unit within the associated cell. The cost c for moving horizontally or vertically between two cells is calculated as: $c = \frac{Cost1 + Cost2}{2} \times d$ where d is the cell resolution (ESRI 2007). For moving diagonally between cells, $c = \sqrt{2} \times \frac{Cost1 + Cost2}{2} \times d$. Assuming a 10 x 10 linear unit cell resolution, the total cost distance of the Euclidean path is 226.27, while the total cost distance of the least-cost path is 102.78.

When considering multiple patches within a landscape, a separate least-cost distance can be determined from each patch to every other patch that is within a specified dispersal (buffer) distance. The dispersal distance is the theoretical maximum linear distance an organism will travel away from a patch (Figure 2). The connectivity score C is based on a combination of the accumulated least-cost path distances, and is calculated for an individual patch p as follows:

$$C_p = \sum_i^n \left(\frac{H_p + H_i}{2} \right) \left(\frac{1000}{d_i} \right) \quad (1)$$

where

- n = number of patches connected to the focal patch
- H_p = habitat value of the focal patch
- H_i = habitat value of connected patch i
- d_i = least-cost edge-to-edge distance between the focal patch and connected patch i

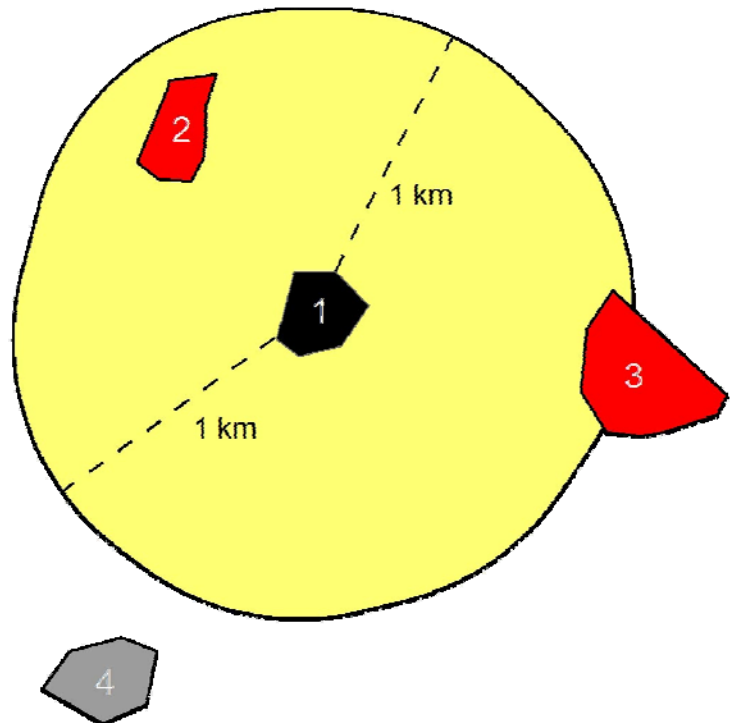
The connectivity score C for a group of patches is then:

$$C = \sum_{p=1}^n C_p$$

C is a unitless, relative measurement that is dependent on the nature of the cost grid and patch habitat values. C values from two different analyses would only be comparable if the two cost grids were of the same resolution, the costs associated with each landscape type were identical, and the scaling of the habitat values was the same. In the first equation, a value of 1000 was used so that C would generally be a number > 1 ; however, because of the relative nature of C , the selection of the value was somewhat arbitrary and could just as easily be any positive number.

Habitat values are a reflection of the quality of the habitat within a specific patch. The values can be scaled in any manner (although a 0.0 – 1.0 scale is suggested for simplicity), and assigned using existing information, determined using various index models such as those based on the Habitat Evaluation Procedure (U.S. Fish and Wildlife Service (USFWS) 1980a, 1980b, 1980c), or simply based on a single metric such as patch size. The effect of habitat values can also be ignored in the calculation of C simply by assigning all patches identical habitat values.

Figure 2. An illustration of connectivity within a specified 1-km dispersal distance. Patches 2 and 3 are within the 1-km dispersal range from focal patch 1, therefore their least-cost distances to patch 1 will be used in the calculation of C_1 . Patch 4 is outside of the dispersal range, therefore its least-cost distance to patch 1 will not be considered.



The cost raster does not necessarily need to be based on land cover, nor does the connectivity score need to be limited to measuring connectivity for animals. Other measurable landscape factors could be used as a replacement for, or in conjunction with, land cover for the purposes of generating the cost raster. For instance, elevation (such as from a digital elevation map) may also be an important factor in determining wildlife movements, and may be a particularly relevant factor for predicting seed dispersal if the connectivity of particular plant communities is of concern.

It should be recognized that although least-cost paths represent the theoretical “best routes” for an organism to traverse, there is no assurance that these are the paths that will actually be used. The trajectory of an organism through a landscape can involve multiple decisions at every point in the route (Brooker et al. 1999); therefore it can be difficult to accurately predict the path using a simple model with only a few variables. This caveat aside, least-cost distances are still more likely to represent the “true” distance between patches than a Euclidean distance would, and are at least a viable first step towards measuring functional connectivity.

SELECTING THE COST GRID: One of the first tasks when conducting a functional connectivity analysis is to create a cost grid, which will vary for different species. Unless the analysis is specifically meant to target a single species, the best way to address connectivity for the entire suite of species that utilize a particular habitat type must be determined. Perhaps the simplest way to address this issue is to create a single cost grid, based largely on best professional judgment, that is assumed to be generally representative for a number of species (i.e., urbanized areas have a greater movement cost than agricultural areas, which have a greater movement cost than forested areas, etc.). Although this approach may be an acceptable method to use for screening and comparative purposes, it is also likely to produce the least accurate results. Another alternative is to use the “extended umbrella” species concept (Hurme et al 2008; Roberge and Angelstam 2004). Under this concept, the species used in the analysis would be one that has some of the most demanding landscape connectivity requirements among species using the targeted habitat. Enhancing connectivity for this species is thus expected to improve connectivity for a number of other naturally co-occurring species that have less stringent landscape requirements. Using an umbrella species, however, requires that there is enough information concerning its dispersal preferences to create an accurate cost grid. The analysis can be made even more robust by using a focal species approach (Lambeck 1997), whereby a suite of umbrella species is used in order to reflect the connectivity requirements of different species guilds (i.e. aquatic, terrestrial, avian). This method, however, can potentially add a considerable amount of time to the analysis and requires information on dispersal characteristics for multiple species.

EXAMPLE APPLICATION: One potential application of the connectivity score is to compare the increases in connectivity resulting from alternative habitat restoration locations. To use a hypothetical example, suppose that two potential locations have been identified as areas for forested habitat restoration within a watershed (Figure 3). Both proposed locations are of similar size and will provide similar on-site habitat value, once restored. However, enough funds are available to purchase and restore only one of these land parcels. Information on how each of these parcels will contribute to connectivity within the watershed, particularly as it relates to migratory birds, can be used to help identify which of them should be targeted for restoration.

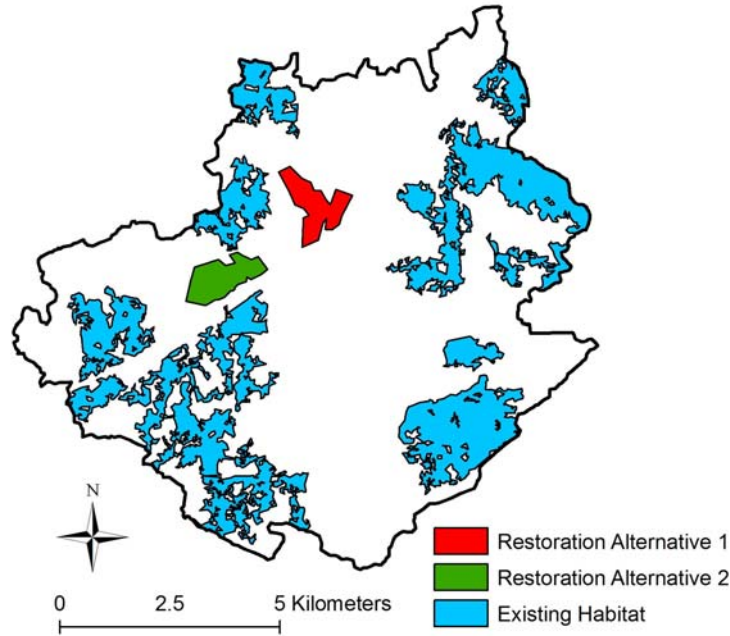


Figure 3. Location of two alternative restoration locations within a watershed.

A cost grid based on land cover (Figure 4) was created using a selected area from the 2001 National Land Cover Database (NLCD) (Homer et al. 2002), which has a 30-m by 30-m cell resolution. The NLCD was reclassified by assigning a cost to each specific land cover (Table 1). The costs were based on values used by Nikolakaki (2004) for the redstart (*Phoenicurus phoenicurus*), an umbrella species of migratory woodland bird found in England which prefers mature, deciduous forest. These cost values were selected purely for demonstrative purposes and to illustrate how values may be derived from the published literature.

Table 1. Cost values for each NLCD land cover class.	
NLCD Class	Landscape Cost Value
Deciduous Forest	1
Mixed Forest	2
Woody Wetlands	2
Evergreen Forest	3
Barren Land	5
Shrub/Scrub	5
Grassland Herbaceous	5
Herbaceous Wetlands	5
Pasture/Hay	10
Cultivated Crops	10
Developed, Open Space	20
Developed, Low Intensity	20
Open Water	25

Existing habitat patches were defined as contiguous areas of deciduous forest that were greater than 50 ha in size, per the habitat requirements *P. phoenicurus* (Nikolakaki 2004). The study watershed contained 12 habitat patches, ranging from approximately 60 to 524 ha in size. For simplicity, the two largest existing habitat patches were assigned habitat values of 1.0 (on a 0 – 1.0 scale), and the remaining habitats were randomly assigned habitat values ranging from 0.3 – 0.9. The two potential restoration sites were both 121 ha, and overlaid existing agricultural land and forested areas that were not large enough to qualify as suitable habitat. The restoration sites were arbitrarily assigned post-restoration habitat values of 0.6.

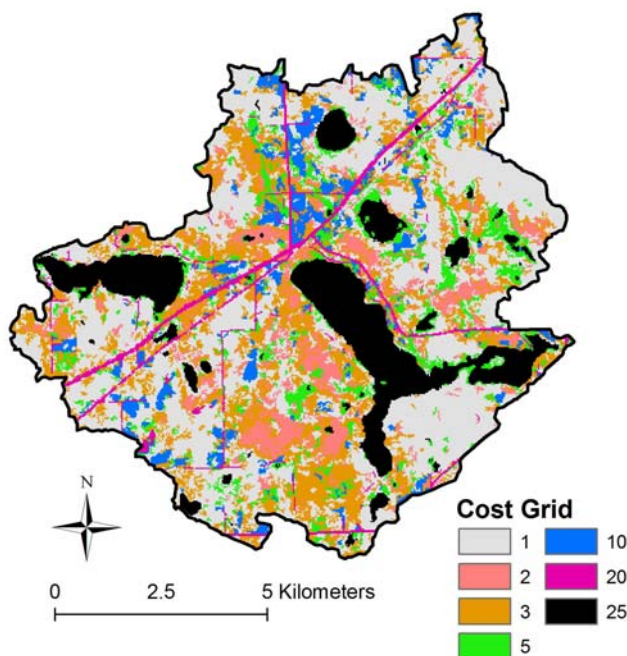


Figure 4. Land cover cost grid used in calculating connectivity scores.

Using the created cost-grid and specifying a 3-km dispersal distance (Nikolakaki 2004), *C* was first calculated for the watershed with neither of the restoration alternatives (baseline condition), and then for the watershed with each of the restoration alternatives (with-project). The results are shown in Table 2. Based on this analysis, alternative 2 will provide more connectivity in the watershed than alternative 1.

Table 2. Total connectivity score and percent increase in the score due to restoration for the three example scenarios.		
Plan	Connectivity Score (<i>C</i>)	Percent Increase in <i>C</i>
Without Restoration	107.6	—
Restoration Alternative 1	111.2	3.3
Restoration Alternative 2	120.9	12.4

C for the watershed is equal to the sum of *C* for each of the individual patches within the watershed. In addition to measuring the change in *C* for the watershed, the change in *C* was also measured for

each of the individual patches for both restoration alternatives. Figure 5 shows the C scores for each of the individual patches in the baseline condition (no restoration), and Figure 6 shows the changes in C for each existing patch resulting from each of the with-project alternatives. As can be seen in these figures, the value of C for a patch can change, even though its nearest neighbor distance remains the same.

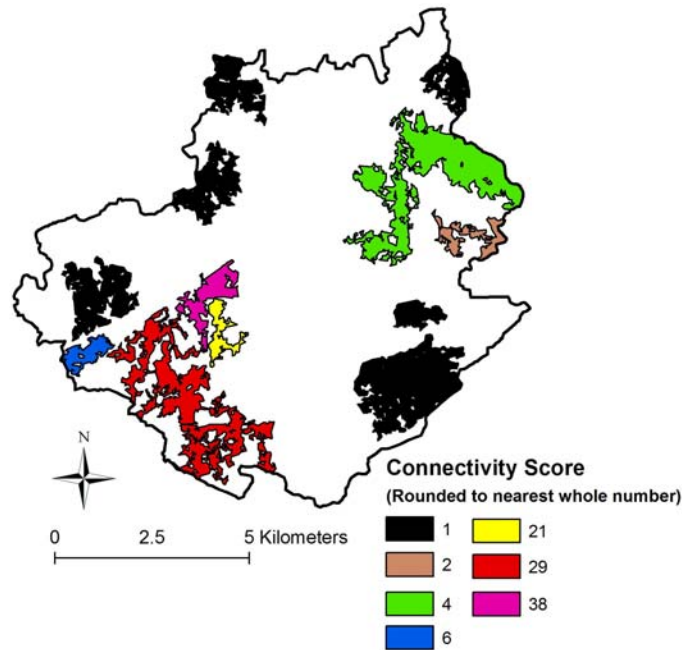


Figure 5. Connectivity scores for individual patches under baseline conditions.

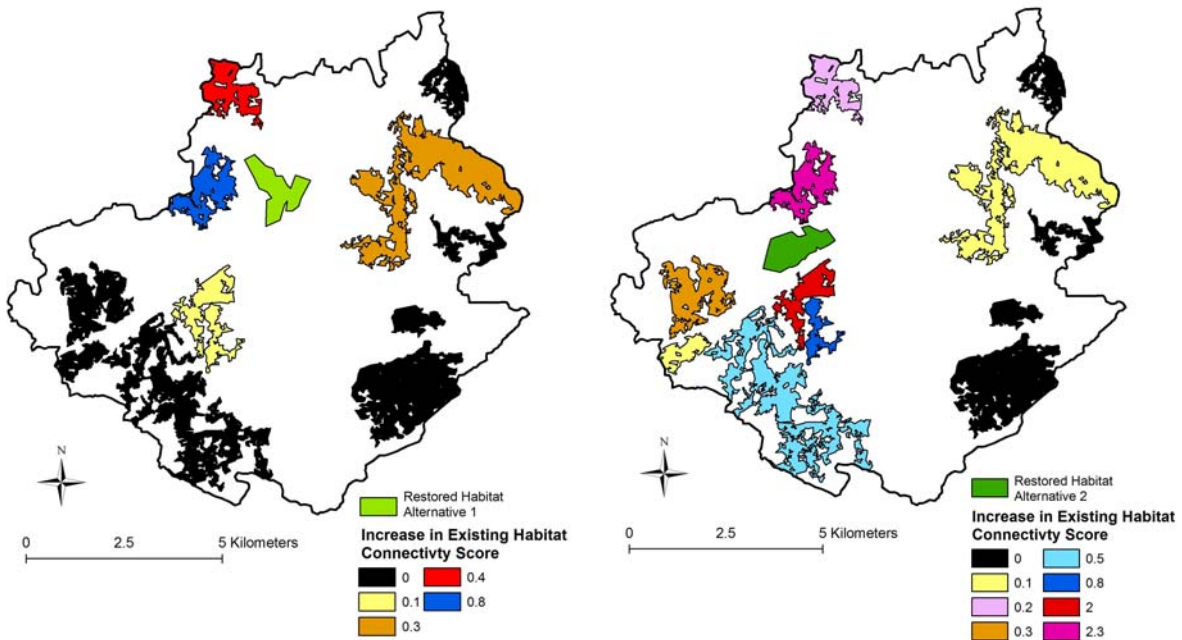


Figure 6. Changes in C to existing habitat patches for each with-project restoration alternative.

This example is meant to illustrate just one possible application for the connectivity score. This type of analysis could be conducted for many other possible scenarios entailing activities that result in an addition or loss of patches, changes in patch habitat value, or changes in the surrounding land cover.

USING THE CONNECTIVITY GIS TOOL: Note: These instructions assume the user has some operational knowledge of ESRI's ArcGIS software, including the ability to execute geoprocessing functions, edit attribute tables, and create new polygons within a shapefile.

Software requirements and installation: The Connectivity GIS tool is a Python script that runs through the ArcGIS Toolbox. It is written to run on ArcGIS Version 9.2 with the Spatial Analyst extension; the script has not been tested on other versions of ArcGIS. Python Version 2.4.x must be installed; the script will not run properly with later versions of Python. The tool can be downloaded as a zip file from <http://el.erd.usace.army.mil/emrrp/gis.html>. Extract the zip file into your C:\ drive. A folder named "Connections tool" will be added to that location. The folder contains a toolbox file (Connectivity Measure.tbx) and a script file (Connectivity.py). Open ArcToolbox through either ArcCatalog or ArcMap. To add the Connectivity tool, right-click on the ArcToolbox heading and select "add toolbox" (Figure 7), then add the "Connectivity Measure" toolbox file.



Figure 7. Adding a toolbox.

Running the tool: Once the toolbox has been added, the connectivity tool can be run by expanding the toolbox and double-clicking on the "Connectivity Measurement Tool" script, which will open the tool dialog screen (Figure 8).

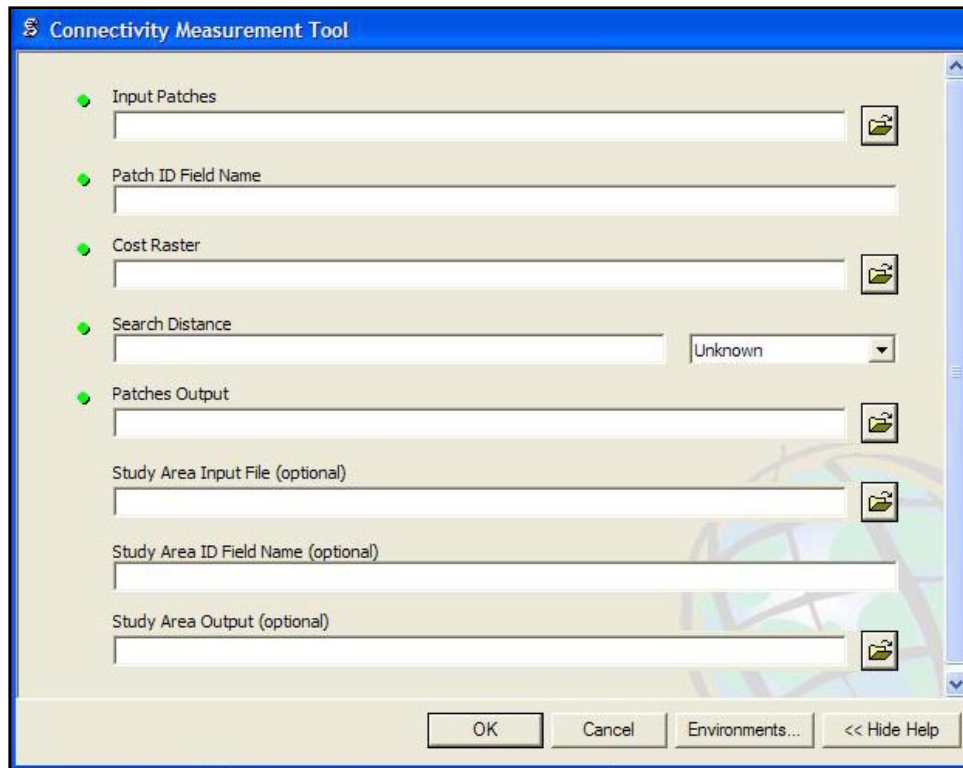
The image shows a software dialog box titled "Connectivity Measurement Tool". It contains several input fields and buttons. The fields are: "Input Patches" (with a file icon), "Patch ID Field Name" (with a file icon), "Cost Raster" (with a file icon), "Search Distance" (with a text box and a dropdown menu set to "Unknown"), "Patches Output" (with a file icon), "Study Area Input File (optional)" (with a file icon), "Study Area ID Field Name (optional)" (with a file icon), and "Study Area Output (optional)" (with a file icon). At the bottom are buttons for "OK", "Cancel", "Environments...", and "<< Hide Help".

Figure 8. Connectivity tool dialog box.

The first line (Input Patches) asks for the shapefile containing the patches being analyzed. The shapefile attribute table must have a column labeled “HV” that contains the habitat value for each patch, and an additional column that assigns each patch a unique, non-zero, identification number. The field name of the column containing the patch identification number is entered into the second line (Patch ID Field Name). Enter the field name exactly as it appears in the attribute table. The third line (Cost Raster) is used to enter the study’s cost raster and the fourth line (Search Distance) is used to enter the dispersal distance. For the distance, enter the number in the first box and then specify the measurement units in the second box. The fifth line is used to enter the name and location of the patches output file created by the tool.

The sixth, seventh, and eighth lines (Study Area Input File, Study Area ID Field Name, and Study Area Output) are used if the user wants to summarize results in a shapefile depicting multiple study areas. If results do not need to be summarized by study area, these last three lines are left blank. If a patch belongs to multiple study areas, its connectivity value will be used in the summary value for each study area it is a part of. The study area shapefile attribute table should contain a column that assigns each study area a unique identification number. The field name of that column should be entered in the “Study Area ID Field Name” line (enter the field name exactly as it appears in the attribute table). The last line is used to enter the name and location to save the study area output file created by the tool.

Creating the cost raster: The simplest method for creating the cost raster is to use the Spatial Analyst “Reclassify” tool on a land cover or other appropriate raster (Figure 9).

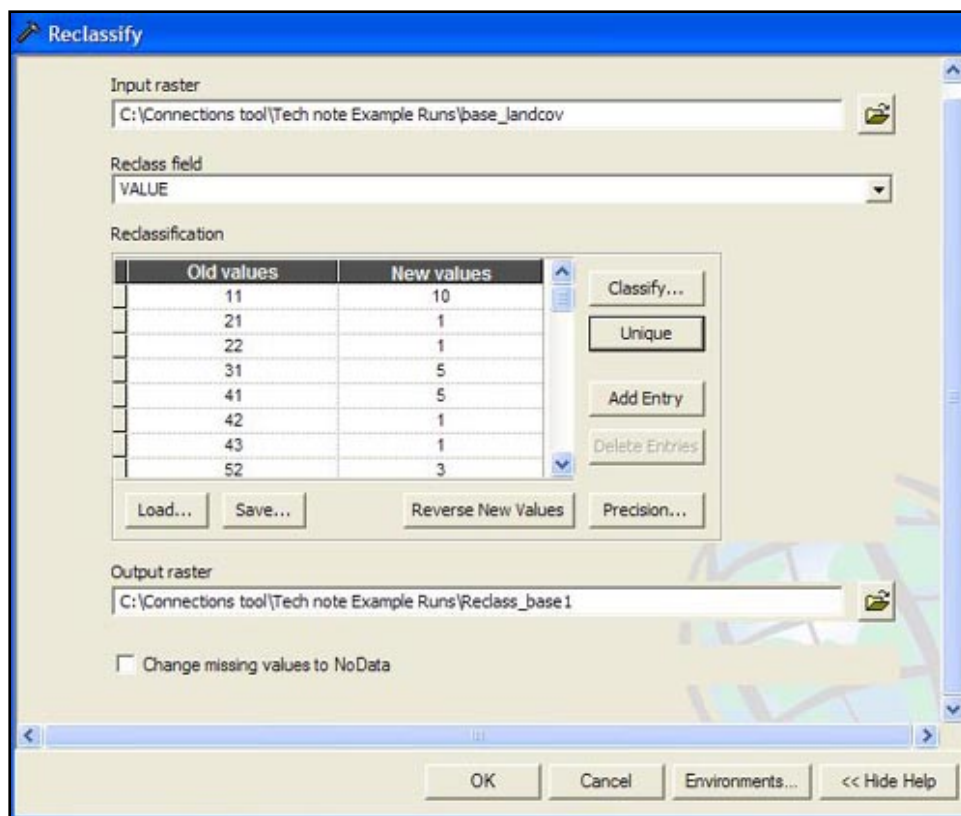


Figure 9. Reclassification tool dialog box.

The “old values” in Figure 9 represent the original land cover codes and the “new values” represent the cost assigned to each land cover. The land cover types that are most easily traversed by the target species should be assigned a cost of 1, with other land cover types assigned a greater value relative to their suitability for a particular species’ dispersal. If a particular land cover type is deemed to be completely impassable for the species it should be assigned a cost of 100,000.

The baseline cost raster can be created using the existing land cover data. A new cost raster must be created for any alternative scenario that results in any changes in land cover. The alternative design cost raster can be created using the following steps:

1. Create a polygon shapefile depicting the proposed land cover changes.
2. Create a new column labeled “Value” in the shapefile. Each polygon in the shapefile with a distinct movement cost should be given a value that is higher than the maximum value assigned to a land cover code in the original land cover raster. If the shapefile contains land covers with different movement costs, the assigned values should be at least an order of magnitude different from one another. For example, if the shapefile contains two land covers with different costs (say, light urban and heavy urban) and the highest land cover code in the land cover raster is 99, then light urban can be assigned a value of 100, and heavy urban can be assigned a value of 1000.

3. Use the “Polygon to Raster” tool to convert the shapefile into a raster. Use “Value” as the value field and set the cell size to be the same as the resolution of the original land cover raster.
4. Use the “Reclassify” tool on this new raster. Make the new values the same as the old values, but change the old value “NoData” to a new value of 0. Before running the reclassification, click on the “Environments” button at the bottom of the dialog box, and enter the original land cover raster under “General Settings” and “Extent.”
5. Use the Spatial Analyst “Plus” tool to combine this new reclassified raster with the original land cover file, creating a new land cover file.
6. Reclassify the new land cover file in the same manner that you created the baseline cost raster. The changed areas will have values that correlate to the values assigned in step 2. Using the example values, the new light urban areas will have values between 101 and 199, and the heavy urban areas will have values between 1001 and 1099.

Processing time: The amount of time it takes to run the tool will depend on the number of patches being analyzed, the complexity of their shapes, and the processing power of the computer being used. For instance, on a 3.2-GHZ processor/3.5-GB RAM computer, it took approximately 2.5 hr to complete an analysis consisting of 235 patches.

Outputs: The tool will output a patches shapefile and, if a study area input file was entered, a study area shapefile. The patches output file will have a “Patch” column that contains the patch ID number, a “Connect” column that contains the connectivity score for each patch, and a “Total” column, which contains the combined connectivity score for all the input patches. The study area output file will have a column (the field name will be the same as that of the ID column in the input file) containing the study area ID numbers and a “Connect” column that contains the total connectivity score for each study area. Columns other than the one containing the study area ID in the input file will also appear in the output file, but the original field names will now have “o_” preceding them.

Miscellaneous tool notes:

- The patch habitat values used would ideally be based on a combination of field and spatial pattern data, and be derived using reviewed methodologies such as HEP. However, in cases where applying a more detailed analysis is unfeasible, useable habitat values can also be generated based solely on spatial pattern data, as was demonstrated in the example application section of this paper. The Patch Calculator (Lin 2007) is an ArcGIS script that can calculate a number of these spatial pattern metrics. The Patch Calculator outputs a shapefile, which can then be used as the input for the Connectivity tool.
- It is recommended that ArcMap or ArcCatalog (whichever one the script is being executed from) be shut down and restarted prior to re-running the tool.
- The cell resolution of the cost raster should be, at minimum, the smallest measurable distance separating two patches in the input shapefile. For instance, if the minimum distance is 10 m, then the resolution of the cost raster should be 10 m by 10 m, or smaller.

- This technical note describes Version 1.0 of the tool. Questions or problems in running the tool should be addressed to the author, Jeff P. Lin, jeff.p.lin@usace.army.mil.

DEALING WITH ISSUES OF HABITAT FRAGMENTATION: The Connectivity score is measured in such a way that, all else being equal, it will increase as the number of suitable habitat patches in the landscape increases, and vice versa. In some analyses, this makes sense, in that connectivity should decrease when existing patches are lost through development, and connectivity should increase when new patches are gained through restoration efforts. On the other hand, it can be counterintuitive when the number of patches is increased by land development projects (via fragmentation of existing patches) or lost through restoration (via combining several smaller patches into a single larger patch).

In the case of fragmentation through development, this issue is partially addressed through the use of habitat values and the cost matrix. In these situations, overall landscape connectivity may still decrease even though the number of patches increases. This decrease in connectivity can result because the new patch fragments will generally have a lower habitat value associated with them, and the cost distance between them will usually be high due to the increased costs of movement in the surrounding landscape. However, if the development project still shows an increase in connectivity over pre-development conditions, the values assigned to the cost matrix may need to be reevaluated, with higher costs assigned to developed areas. Another alternative in this situation is to divide *C* by the total number of patches, and use that value as the comparison metric for with- and without-project conditions.

The alternative situation, one in which restoration results in a decrease in the total number of patches, can be handled in a different manner. In this case, the original set of pre-restoration patches should be used as the input in both with- and without-project analysis. However, in the with-project analysis, the habitat values of the affected patches can be changed to reflect what the value would be in the larger, post-restoration patch that they are now part of. Also, the post-restoration cost matrix should be changed so that the cells being restored are assigned a cost value of 1. This process is illustrated in Figure 10.

CONCLUSION: The connectivity score presented in this technical note can be used as a way to measure and compare functional connectivity among groups of habitat patches. The accompanying GIS tool can be used as an easy and automated way to calculate the score, and can potentially be utilized in cost or benefit analyses of alternatives in a wide variety of land development or restoration plans. Although the connectivity score represents a theoretical improvement over many currently used measures of connectivity, it has yet to be compared against real world species dispersal data. Therefore, further research is required to validate the results of the tool's application.

ACKNOWLEDGEMENTS: Research presented in this technical note was developed under the Environmental Benefits Assessment (EBA) research area of the Ecosystem Management and Restoration Research Program (EMRRP). The U.S. Army Corps of Engineers (USACE) Proponent for the EBA research area is Rennie Sherman. The EMRRP Program Manager is Glenn Rhett and the Technical Director is Dr. Al Cofrancesco, both of the ERDC Environmental Laboratory.

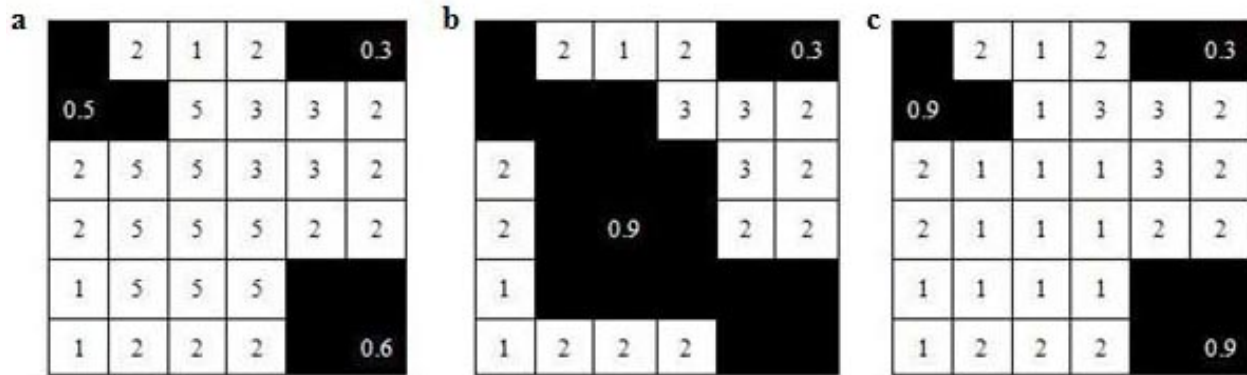


Figure 10. How to conduct the connectivity analysis when, due to the combination of existing patches, the total number of patches in the landscape decreases. Grid a shows the landscape pre-restoration, where the black areas are existing habitat patches. The numbers in the black areas are the habitat value of the patch, the other numbers are the cell movement costs. Grid b shows the landscape after areas have been restored. Two of the patches have been joined to form one larger patch, which now has a higher habitat value. Grid c shows how the inputs for the with-project analysis should look. The patches are the same as in grid a; however, the habitat value of the larger patch in grid b is now utilized. Also, the cost grid is changed so that the cells that would be encompassed by the new patch area now have a cost of 1.

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Lin, J. P. 2008. *A metric and GIS tool for measuring connectivity among habitat patches using least-cost distances*. EMRRP Technical Notes Collection. ERDC TN-EMRRP-EBA-02. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

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